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BEARING EVALUATIONS AND SLIDING TESTS ON BORIDE COATINGS AND COMPOUNDS

August 1976

U.S. ARMY ARMAMENT COMMAND

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

TECHNICAL REPORT

AMCMS No. 3297.06.7550

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Wear tests, consisting of journal bearing tests and sliding friction tests, were conducted on bonded specimens produced by electrochemical deposition from a fused salt and on specimens made from boride powders ($Cr Br_2$, VB_2, and MoB_2).

Friction values and wear resistance were determined for the specimens. In general, the steels which were borided showed better wear resistance than comparable non-borided steels.

(See Other Side)

20.

No consistent correlation was obtained between crystal structure and sliding performance.

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INTRODUCTION

An overall study is being made to determine the feasibility of improving the wear and erosion resistance of gun components by the use of boride coatings on the steel surfaces (Ref 1). As one phase of this work, an experimental investigation has been conducted on the friction and wear characteristics of borided steel sleeve bearings operating in the boundary region of lubrication at slow speeds and high loads (Ref 2). The results of those slow speed tests demonstrated that steels that had been exposed to the boriding process wore in to form highly polished contact areas and, in general, performed more effectively than non-borided steels of the same hardness level. It was hypothesized that those results were due to the fact that the boriding process had formed surface compounds having hexagonal crystal structures. Several investigators (e.g., Refs 3 and 4) have shown that materials with this crystal structure will generally tend to give lower friction and surface damage during sliding.

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1. V. J. Colangelo and B. A. Fosnocht, "Feasibility of Boriding Alloy Steels at Temperatures Below 1000°F", WVT-TR-75012, March 1975.

2. S.F. Murray, "Effect of Boriding on Bearing Wear and Lubrication", WVT-CR-75004, January 1975.

3. M. Sikorski, "Correlation of the Coefficient of Adhesion with Various Physical and Mechanical Properties of Metals", Trans. ASME. Vol. D85 (1963) p. 279.

4. D. H. Buckley and R. L. Johnson, "Influence of Crystal Structure on Friction Characteristics of Rare-Earth and Related Metals in Vacuum to 10^{-10}mm of Mercury", ASLE Trans. Vol. 8 (1965) p. 123.

Because run-in effects, particularly improvements in surface finish, are of major importance in lubrication, this work was expanded to study the effect of run-in on bearing performance at higher sliding velocities. Friction vs velocity curves were run using both borided and non-borided steel sleeve bearings lubricated with SAE 10W petroleum oil. In addition to these bearing tests, sliding friction bench tests were also run, using pure boride powders encapsulated in a plastic matrix as the slider specimens, to determine if specific boride compounds were particularly effective in reducing friction and wear.

The purpose of this report is to describe the results that were obtained.

TEST EQUIPMENT

The journal bearing tests were run using a Dow Corning LFW-5 Journal Bearing Testing Machine. In this machine a test shaft, supported on two pillow block ball bearings, is driven by means of a variable speed motor. The test bearing is retained in a steel housing and is mounted on the shaft between the support bearings. Load is applied by means of dead weights acting through a lever arm to load the test bearing down against the shaft. Torque is measured by means of a flexure arm on which strain gages are mounted. Bearing temperatures are measured by a thermocouple which contacts the outer diameter of the test bearing in the loaded region.

The sliding friction tests were run with a Dow Corning LFW-6 Test Machine. In this test rig, three 1/4" diameter sliders are dead-weight loaded against the surface of a 1.25" diameter thrust washer by means of a lever arm arrangement. The sliders are retained in a rotating holder. The thrust washer is mounted in a housing which is supported on ball bearings so that the torque can be measured.

TEST SPECIMENS

a. Journal Bearing Tests

The steel used for the bearing tests had the following nominal composition:

0.35 Carbon
0.38 Manganese
0.21 Silicon
3.0 Nickel
0.9 Chromium
0.6 Molybdenum
0.11 Vanadium

A number of steel sleeve bearings, which had been borided by the G.E. Metalliding process, were used in this study. These bearings had a nominal I.D. of 0.75" and were 1" long. The projected bearing area (LxD) was 0.75 sq inches. Stress, in psi, is normally determined by dividing the load by the projected area.

Originally, these specimens had been processed at various times, temperatures, and current densities to determine if a boride layer of significant thickness could be obtained at a temperature of 1000°F, or lower (Ref 1). It had been shown, by metallurgical cross-sectioning of the specimens, that no visible boride coating was formed on this steel at a processing temperature of 1000°F. The minimum practical temperature required

1. V. J. Colangelo and B. A. Fosnocht, "Feasibility of Boriding Alloy Steels at Temperatures Below 1000°F", WVT-TR-75012, March 1975.

to form a boride layer 0.0005" thick was found to be 1250°F for this alloy steel.

Boriding the steel at 1250°F resulted in over-tempering of the substrate and a drop in hardness from 37 R_c to 22 R_c. Thus, there were a number of material variables in these tests including:

a. Exposure to the boriding process.

b. The presence of a visible boride layer.

c. Over tempering of the substrate.

The bearing evaluations were concentrated on the extreme cases, i.e., the steel bearings which had the thickest boride films, and the steel bearings that had been processed at the minimum boriding temperature of 1000°F and which had no visible boride layer. The following specimens were evaluated:

Sample No.	Boriding Temp.	Boriding Time	C.D. ma/cm^2	Orig. Hardness	Final Hardness	Coating Thickness mils
001	1000°F	20 Hrs.	2.30	37	37	0
002	1000°F	20	1.15	37	37	0
251	1250°F	20	2.30	38	22	0.5
252	1250°F	20	1.15	37	22	0.5

In addition, plain, non-borided steel sleeves of the same alloy composition were fabricated and heat treated to the same hardness levels (37 R_c and 22 R_c) as the borided sleeve bearings, to determine if the substrate hardness would have a significant effect on the test results. The test shafts were all M-2 tool steel which had been hardened from 58 to 60 R_c and ground to a finish of 12 micro-inches CLA.

It should be noted that a diametral clearance of 0.004" was used in these tests. This is a very large clearance for a fluid film bearing of this size, but the bearing and shaft dimensions were originally selected for the high load, low speed tests and it would have been too costly to remake the specimens with tighter clearances for the higher speed runs. In any event, the goal of this work was to study run-in phenomena rather than fluid film performance. The main effect of the large clearances was to minimize fluid film effects, even at high sliding velocities.

b. Sliding Friction Tests

For the sliding tests, the slider specimens were fabricated by mixing the pure test powders with a phenolic molding powder and compacting the mixture in special dies using a heated metallurgical mounting press. The test powders were all typically 99% purity and -325 sieve size. To concentrate these hard particles as much as possible at one end of the slider specimen, the phenolic molding powder was sieved to the same size as the test powder (-325 mesh) and was then mixed with the test powder in the proportion 2 parts of molding powder to one part of test powder (higher concentrations of test powder resulted in poorly bonded samples). The 2-1 mixture was then placed in the bottom of the die, and the rest of the die was filled with phenolic molding powder. This was compacted under pressure at 300F.

Oil-hardened drill rod flats were used for the flat washer specimens. These washers were hardened to 60 R_c and were surface ground to a finish of about 16.

TEST PROCEDURE

Prior to assembly, the sleeve bearings and shafts were washed in mineral spirits to remove residual lubricant films or other contaminants. Oil was applied to the bearing and shaft surfaces before they were assembled and a drop of oil was applied to each side of the bearing at periodic intervals so that a meniscus of lubricant was always visible at each end of the bearing during the tests. Surface tension retained the lubricant and capillary action kept the bearing supplied with oil.

A non-detergent petroleum oil, SAE 10W, was used as the lubricant. In the sliding tests, no attempt was made to clean the slider specimens. They were used just as they were fabricated. The test powder was covered by a layer of the phenolic molding powder at the start of the test, but this surface layer was quickly worn away to expose the hard particles in the plastic matrix. An attempt was made to run this test with no lubricant present, but this resulted in the formation of considerable reddish brown wear debris (Fe_2O_3) from the steel flat washer specimen, so all subsequent tests were run with Stoddard solvent as the lubricant. This is a proprietary solvent with a low viscosity and very little boundary lubrication capability.

Each of the slider specimens was evaluated by running a three hour test at a load of 30 pounds and a sliding velocity of 16 feet/minute. This load applied a nominal stress of 200 psi to each slider tip.

Because of the volatility of the Stoddard solvent, and the fact that the surface of the molding powder had to be worn away before the hard particles were exposed, the test was stopped every 10 minutes, wear debris was wiped off of the surfaces and the specimens were relubricated with fresh solvent.

Microscopic examinations of the sliders and discs were made after the test and Talysurf traces were made of the disc surfaces. The specimens were then photographed for future reference.

The three best material combinations were then re-evaluated to determine the effect of load on performance. This was done by running a series of ten minute friction tests at loads ranging from 10 to 100 pounds (67 to 670 psi) in 10 pound increments.

TEST RESULTS

a. Journal Bearing Tests

The original test plan was to run a series of friction-velocity cycles on each bearing and, every 25 cycles, to measure friction in 100 rpm increments of shaft speed over the speed range from 0 to 1740 rpm. Thus, a series of friction-velocity curves would be obtained showing the effect of running time on the bearing. If polishing and improved lubrication occurred, it would be expected that after a given number of cycles the borided surfaces would show lower friction than the non-borided surfaces. More specifically, the critical velocity, where friction changes from boundary lubrication to hydrodynamic lubrication, would occur at a lower velocity. In addition to the friction-velocity curves, surface profilometer traces were to be made of the worn areas at the conclusion of the test.

A number of bearing tests were run to evaluate this approach, but only the non-borided steel bearings showed any significant changes in the friction-velocity curves with run-in time. Examination of the contact areas on the bearings after these tests showed that the non-borided bearings had indeed run-in to form polished contact areas, but that practically no run-in had occurred on the borided bearings, even those with no detectable boride layer. The surfaces were too wear-resistant.

Tests were then made to determine if long time, continuous running at selected loads and speeds could be used to wear in the borided specimens. After several days of running at low stress levels (less than 300 psi) and speeds from 150-300 rpm, very little wear was observed. The bearings simply wore in just enough to accommodate the imposed load.

Partial run-in was finally achieved by selecting load and speed conditions which would drive the bearing temperature up above 200F by frictional heating. This required stress levels in the 400 psi to 600 psi range and speeds on the order of 360 rpm. At high temperature, the viscosity of the SAE 10 oil was apparently so low that fluid film effects were minimized. Even then, it was not possible to demonstrate that the borided steel had any advantages over the non-borided steel, since the latter bearings ran-in much faster (because of higher wear rates) and, even after several days of running, the borided bearings had still not completely run-in.

In this present series of tests, the only advantage that the borided bearings showed over the non-borided bearings was the fact that they did not fail at higher loads during the initial stages of run-in before a smooth, conforming area could be worn on the bearing surfaces. This is demonstrated by the friction data shown in Tables 1A to 1D and the surface finish data given in Table 2. These four test bearings were set-up and, without any attempt to run-in the bearings, friction-velocity curves were run at four loads: 200, 300, 400 and 500 pounds. Both of the non-borided steel bearings seized under the 500 pound load. The harder ($37R_c$) bearing seized at 1740 rpm, while the softer ($22R_c$) bearing seized at about 1200 rpm. In contrast, both of the borided bearings survived this initial stepwise loading test and, after going through subsequent run-in procedures (at higher temperatures), these bearings showed an improvement in performance.

The results of these higher speed bearing tests substantiated the conclusion that was drawn in the previous work (Ref 2) that steels which had been exposed to the boriding process gave improved

2. S.F. Murray, "Effect of Boriding on Bearing Wear and Lubrication", WVT-CR-75004, January 1975.

TABLE 1A. SLEEVE BEARING TEST RESULTS

Friction-Velocity Results as a Function of Load

Test Bearing : #251 Borided (Detectable layer)

Initial Friction Values

Speed	Load 200 lbs. (275 psi)	300 lbs. (410 psi)	400 lbs. (550 psi)	500 lbs. (685 psi)
30 rpm	.083	.073	.080	.078
150	.070	.040	.048	.055
360	.033	.030	.035	.042
590	.026	.028	.033	.038
800	.025	.027	.030	.036
920	.023	.027	.033	.038
1200	.023	.027	.034	.039
1450	.023	.028	.035	.041
1650	.023	.030	.039	.046
1740	.023	.032	.043	.050

After First Run-in at Higher Temperature

Speed	200 lbs.	300 lbs.	400 lbs.	500 lbs.
30 rpm	.040	.070	.080	.057
150	.025	.042	.029	.030
360	.020	.028	.026	.028
590	.019	.026	.025	.027
800	.019	.023	.024	.026
920	.020	.023	.023	.025
1200	.020	.023	.024	.024
1450	.020	.023	.024	.024
1650	.020	.023	.024	.024
1740	.021	.024	.024	.024

After Second Run-in at Higher Temperature

Speed	200 lbs.	300 lbs.	400 lbs.	500 lbs.
30 rpm	.065	.050	.085	.086
150	.023	.025	.034	.041
360	.018	.020	.025	.030
590	.018	.020	.025	.028
800	.018	.020	.025	.027
920	.018	.020	.025	.027
1200	.018	.020	.024	.026
1450	.018	.020	.024	.026
1650	.018	.020	.024	.025
1740	.018	.020	.024	.025

TABLE 1B. SLEEVE BEARING TEST RESULTS

Friction-Velocity Results as a Function of Load

Test Bearing : #002 Borided (No Detectable Layer)

Initial Friction Values

Speed	Load 200 lbs. (275 psi)	300 lbs. (410 psi)	400 lbs. (550 psi)	500 lbs. (685 psi)
30 rpm	.088	.092	.090	.086
150	.047	.065	.073	.075
360	.023	.040	.053	.062
590	.021	.027	.040	.054
800	.021	.025	.029	.046
920	.022	.025	.028	.040
1200	.022	.025	.028	.035
1450	.022	.026	.028	.030
1650	.023	.026	.028	.027
1740	.023	.026	.028	.026

After First Run-in at Higher Temperature

Speed	200 lbs.	300 lbs.	400 lbs.	500 lbs.
30 rpm	.090	.083	.086	.084
150	.038	.032	.039	.040
360	.018	.025	.034	.034
590	.011	.023	.029	.030
800	.011	.023	.026	.025
920	.012	.023	.026	.025
1200	.012	.023	.026	.025
1450	.014	.023	.026	.025
1650	.014	.023	.026	.025
1740	.014	.023	.026	.025

After Second Run-in at Higher Temperature

Speed	200 lbs.	300 lbs.	400 lbs.	500 lbs.
30 rpm	.080	.087	.090	.068
150	.032	.022	.025	.030
360	.012	.021	.023	.027
590	.010	.021	.023	.026
800	.010	.021	.023	.024
920	.011	.021	.023	.024
1200	.011	.021	.023	.024
1450	.011	.021	.023	.024
1650	.011	.021	.023	.024
1740	.011	.021	.023	.023

TABLE 1C. SLEEVE BEARING TEST RESULTS

Friction-Velocity Results as a Function of Load

Test Bearing : # 001 (37 Rc) Not Borided

Initial Friction Values

Speed	Load 200 lbs. (275 psi)	300 lbs. (410 psi)	400 lbs. (550 psi)	500 lbs. (685 psi)
30 rpm	.095	.097	0.10	0.10
150	.068	.073	.079	.080
360	.046	.057	.063	.070
590	.035	.044	.051	.060
800	.025	.032	.040	.052
920	.025	.026	.034	.050
1200	.025	.025	.029	.054
1450	.025	.024	.026	.066
1650	.025	.024	.025	.079
1740	.025	.024	.025	- SEIZED -

After First Run-in at Higher Temperature

Speed	200 lbs.	300 lbs.	400 lbs.	500 lbs.
30 rpm				
150				
360				
590	BEARING	FAILED		
800				
920				
1200				
1450				
1650				
1740				

After Second Run-in at Higher Temperature

Speed	200 lbs.	300 lbs.	400 lbs.	500 lbs.
30 rpm				
150				
360				
590				
800				
920				
1200				
1450				
1650				
1740				

TABLE 1D. SLEEVE BEARING TEST RESULTS

Friction-Velocity Results as a Function of Load

Test Bearing : #003 (22 Rc) Not Borided

Initial Friction Values

Speed	Load 200 lbs. (275 psi)	300 lbs. (410 psi)	400 lbs. (550 psi)	500 lbs. (685 psi)
30 rpm	.088	.095	.096	.094
150	.061	.068	.074	.078
360	.038	.050	.058	.066
590	.020	.032	.045	.051
800	.017	.020	.026	.046
920	.017	.019	.022	.070
1200	.017	.019	.022	-SEIZED-
1450	.017	.019	.022	
1650	.017	.019	.021	
1740	.017	.019	.021	

After First Run-in at Higher Temperature

Speed	200 lbs.	300 lbs.	400 lbs.	500 lbs.
30 rpm				
150				
360	BEARING FAILED			
590				
800				
920				
1200				
1450				
1650				
1740				

After Second Run-in at Higher Temperature

Speed	200 lbs.	300 lbs.	400 lbs.	500 lbs.
30 rpm				
150				
360				
590				
800				
920				
1200				
1450				
1650				
1740				

TABLE 2. CONDITION OF BEARINGS AFTER TEST

1. Bearing #251 - Borided, detectable layer

Bearing	Journal
Original finish 19-24	Orig. finish 12-14
Final finish 33 (Smooth plateaus and deep scratches)	Final finish 2-3

Wear area on bearing only partially run-in

---

2. Bearing #002 - Borided, no detectable layer

Bearing	Journal
Original finish 38-42	Orig. finish 12-14
Final finish 28 (Smooth plateaus and deep scratches).	Final finish 6-7

Wear area on bearing shows slightly more contact than #251, but only partial run-in.

---

3. Bearing #001 (37Rc) - Hardened but not borided

Bearing	Journal
Orig. finish 16	Orig. finish 12-14
Final finish 132	Final finish 30-42

Bearing seized during initial test. Deep scratches and material transfer in center of load zone.

---

4. Bearing #003 (22 Rc) - Not borided

Bearing	Journal
Orig. finish 11	Orig. finish 12-14
Final finish 120	Final finish 32-40

Bearing seized during initial test. Same appearance as #001 (37Rc).

sliding behavior even when no detectable boride layer was formed. They also demonstrated that the borided steels were significantly more wear-resistant than the non-borided steels of the same composition and hardness level. However, they also showed that boriding was only effective when the test conditions were such that bearing performance was very marginal. Under less stringent conditions, the borided bearings would wear in very slowly. In many applications where fluid film effects predominate, this could be a disadvantage. However, in mechanical devices, such as heavily-loaded, slow speed gears or bearings, where considerable metal to metal contact would be anticipated, the boride coatings should offer considerable advantage.

b. Sliding Test Results

Table 3 lists the compounds that were evaluated and their crystal structure classification. This table also summarizes the frictional data and the condition of the hardened steel discs after the three hour test at a 30 pound load was concluded. One test was run as a blank using slider specimens that were made from straight molding powder with no hard particles in the matrix. In general, all of the specimens which contained hard particles showed much better frictional characteristics than the straight molding powder.

The surface finish measurements of the discs, which were taken after the tests, showed no clear-cut correlation with the friction

TABLE 3. SUMMARY OF FRICTION TEST RESULTS ON VARIOUS HARD PARTICLES MOLDED IN PLASTIC MATRIX

Lubricant - Stoddard Solvent

Load - 30 pounds Speed - 16 feet/minute

Test time - 3 hrs. Mating Surface - Hardened drill rod

Powder	Crystal Structure	Range of Friction Values	Damage to Disc Appearance	Highest Peak (in micro-inches)	Deepest Scratch (in micro-inches)
Straight Plastic	-	0.18-0.6 (erratic, decreasing after 2 hours)	Slight polishing	21	20
MoB_2	H[a]	0.085-0.12 (two higher peaks)	Slight polishing	12	43
CrB_2	H	0.08-0.24 (decreasing with time to 0.08-0.14)	Appears to be polishing, few scratches	51	108
VB_2	H	0.085-0.16 (one high peak)	Isolated scratch	83	40
TiB_2	H	0.12-0.45 (erratic, average about 0.3)	Sharp scratches	42	107
TiC	C	0.17-0.29 (generally about 0.25)	Several scratches	105	102
B_4C	R	0.13-0.36 (erratic, average 0.25	Smooth wear	80	62
SiC	Not Certain	0.16-0.28 (generally 0.23)	Many fine scratches	42	30
Cr_2O_3	H	0.14-0.27 (generally 0.23)	Appears to be polishing	36	52

(a) H = hexagonal
R = rhombohedral
C = cubic

coefficients. The titanium carbide composite appeared to cause the most damage while the molybdenum diboride gave the least amount of abrasion.

Figure 1 shows the coefficient of friction vs time for the best three materials, CrB_2, VB_2 and MoB_2.

Photographs of typical slider and disc surfaces are shown in Figure 2.

Figure 3 shows the effect of load on the best materials. Observations of the slider specimens, which were made each time the load was changed, indicated that the effect of load on slider wear was minimal after the initial wear area was formed.

It is obvious that the best results (disk polishing, low friction) were obtained with the hexagonal borides Mo, Cr, and Va. However, titanium boride which is also hexagonal gave poor results and boron carbide which is rhombic gave smooth wear rather than scratching of the steel. Thus, the correlation with the hexagonal structure could not be firmly established. It should also be noted that the borides of Mo, Cr, and Va are softer than most of the other materials in Table 3 (H_v = 1000 to 2000 Vickers); thus, they would be expected to give less damage. On the other hand, B_4C is the hardest material used.

While these sliding test results must be considered as preliminary data, they do serve to illustrate that particular chemical

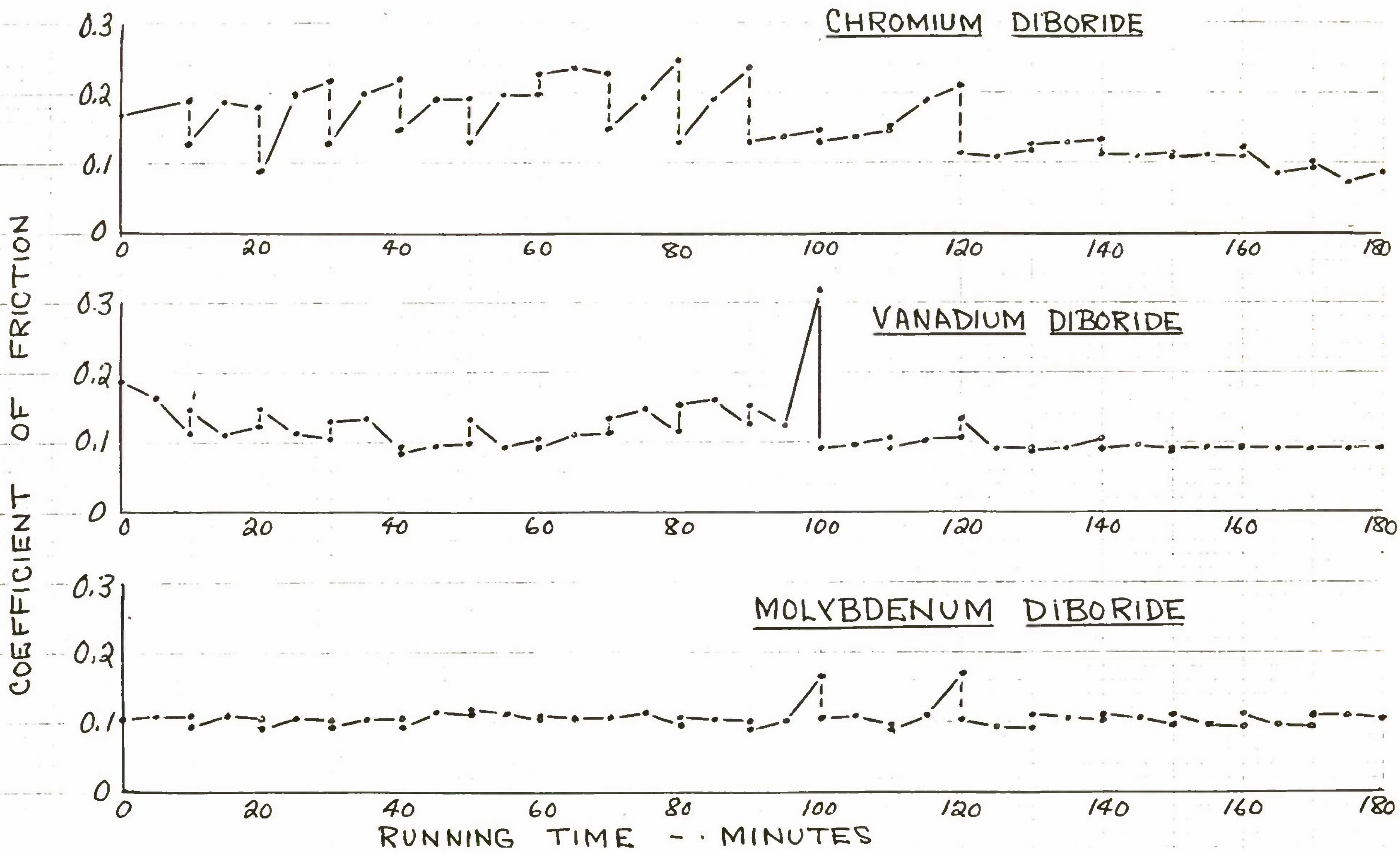
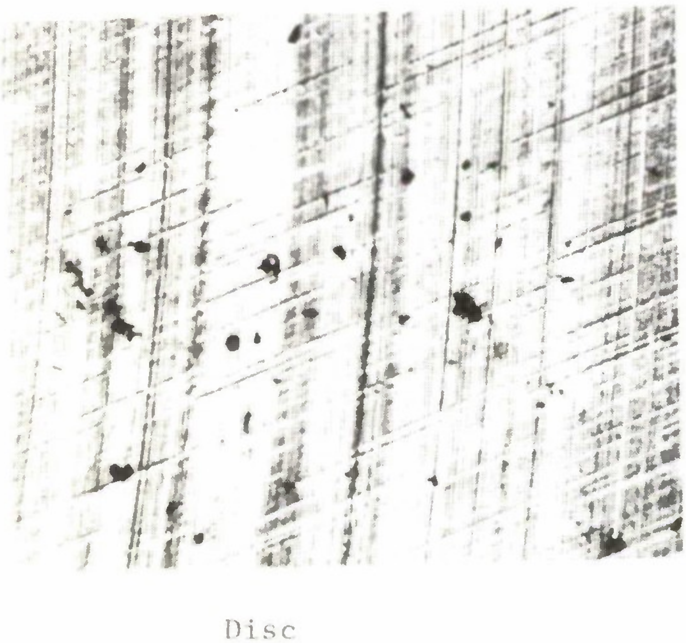


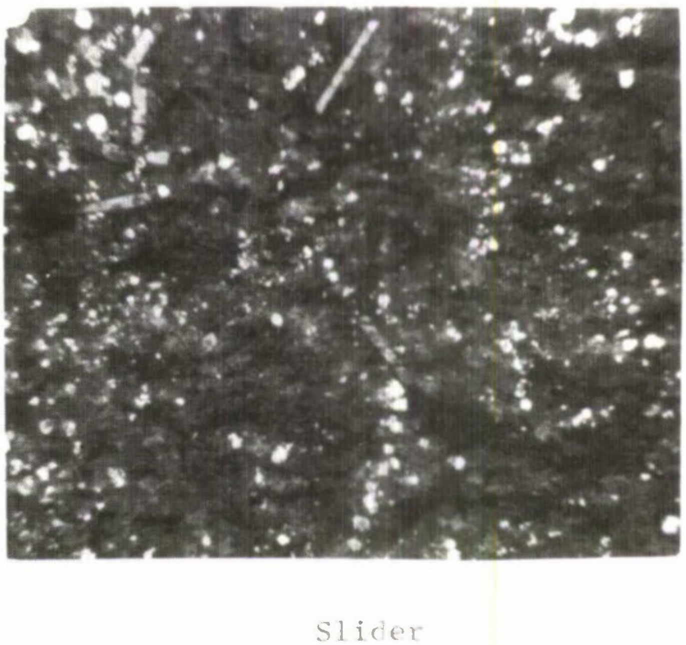
Figure 1. Effect of time on sliding friction. Lubricant - Stoddard solvent. Load - 30 pounds. Sliding velocity - 16 ft/min. Mating surface - hardened drill rod.

Disc

Slider

Chromium Diboride





Disc

Slider

Molybdenum Diboride

Figure 2. Typical appearance of slider and disc specimens.

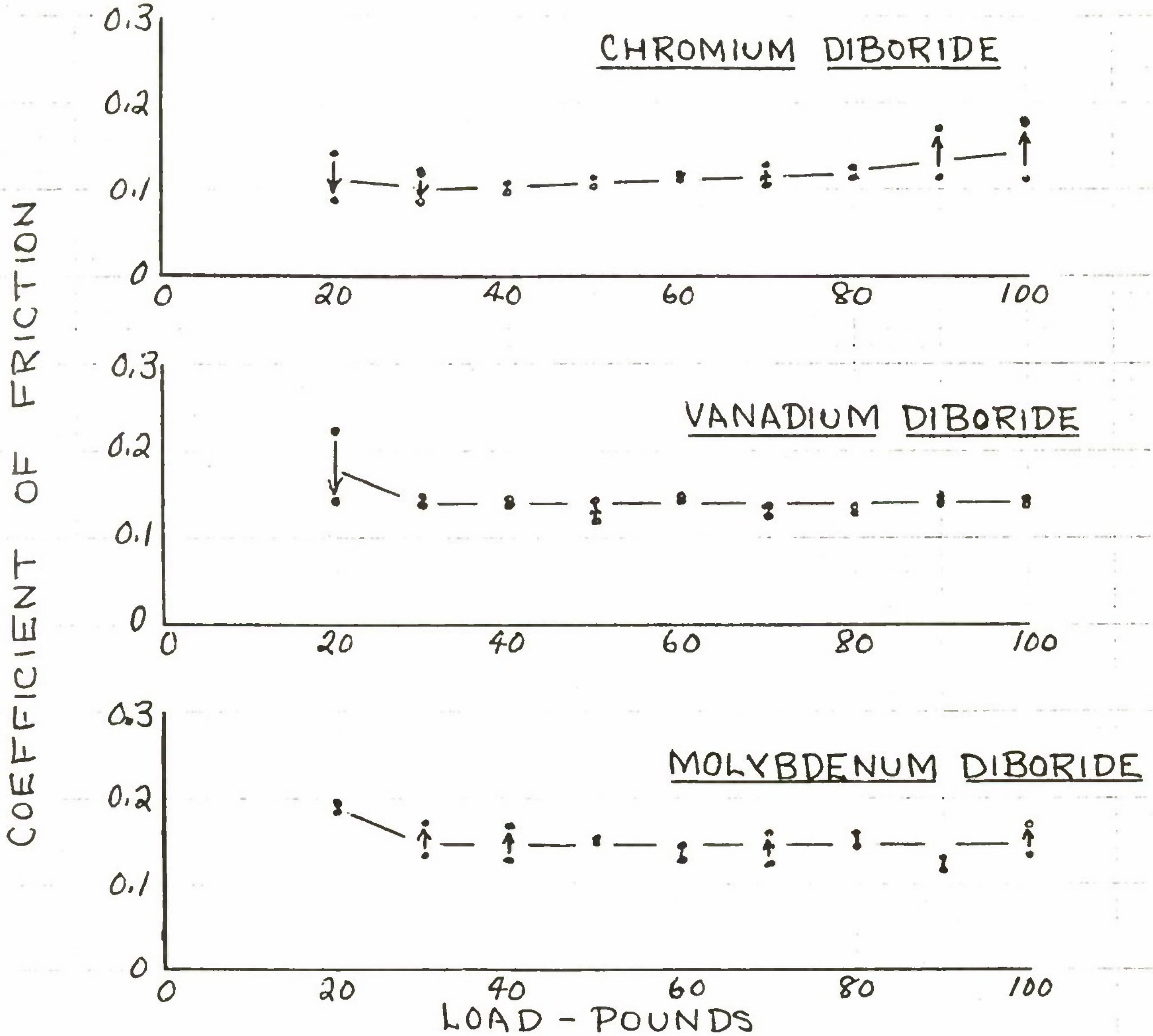


Figure 3. Effect of load on friction. Lubricant - Stoddard solvent. Sliding velocity - 16 ft/min. Time - 10 min at each load. Mating surface - hardened drill rod.

compounds can have a significant effect on the friction and wear characteristics of bearing materials. It is of importance to note that many of these compounds would be expected to be present in the surface layer of a borided alloy steel.

CONCLUSIONS

a. Journal Bearing Tests

Steels which have been exposed to the boriding process have significantly better wear resistance than non-borided steels of the same substrate hardness. No obvious difference in friction or wear characteristics was observed between steels that were borided at 1250°F to form a surface layer 0.5 mils thick and steels that were borided at 1000°F and had no visible boride layer. This latter conclusion is reinforced by the results reported in Ref 2.

Boriding will not improve the performance of light to moderately loaded bearings which operate primarily in the full fluid film region. The surfaces are too wear-resistant to run-in under these conditions.

Under marginal operating condition, such as high loads or low speeds, the boride coatings are beneficial in minimizing welding and material transfer.

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2. S.F. Murray, "Effect of Boriding on Bearing Wear and Lubrication", WVT-CR-75004, January 1975.

b. <u>Sliding Friction Tests</u>

Three samples of pure boride powders, CrB_2, VB_2, and MoB_2, gave low friction values (generally in the range from 0.10 to 0.15) when these powders were molded in a plastic matrix and were run against hardened steel with Stoddard solvent as the lubricant. All of these compounds have hexagonal crystal structures and are presumed to be present in the surface layer of the borided steel bearings. Metallurgical investigations should now be conducted to determine the exact composition of the borided surface.

Several other hard compounds were also evaluated in these sliding tests. These materials all gave friction values in the range from 0.16 to 0.4. Their frictional characteristics were more erratic than the first three samples. Some of these had hexagonal structures while others were cubic or rhombohedral.

As yet, no consistent correlation of crystal structure versus sliding performance has been established; however, certain materials did give improved performance over others.

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3. M. Sikorski, "Correlation of the Coefficient of Adhesion with Various Physical and Mechanical Properties of Metals", Trans. ASME. Vol. D85 (1963) p. 279.

4. D. H. Buckley and R. L. Johnson, "Influence of Crystal Structure on Friction Characteristics of Rare-Earth and Related Metals in Vacuum to 10^{-10}mm of Mercury", ASLE Trans. Vol. 8 (1965) p. 123.

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